AD/A-005 828

MARINE PHYSICS: INTERNAL-SURFACE WAVE INTERACTION AND MICROSTRUCTURE MEASUREMENT PROGRAM

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Scripps Institution of Oceanography

Prepared for:

Advanced Research Projects Agency
Office of Naval Research

31 December 1974

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: SIO Reference Number 75-3

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER: AD/A005 828

4. TITLE (and Subtitle): MARINE PHYSICS: INTERNAL-SURFACE WAVE INTERACTION AND MICRO-STRUCTURE MEASUREMENT PROGRAM

5. TYPE OF REPORT & PERIOD COVERED: Technical Progress 7/1/74 - 12/31/74

6. PERFORMING ORG. REPORT NUMBER: AOEL Report No. 68

7. AUTHOR(s): I. Charles S. Cox, Robherd E. Lange & Michael C. Gregg; II. James L. Cairns & Gordon O. Williams; III. Carl H. Gibson, Frank H. Champagne & Carl A. Friehe

8. CONTRACT OR GRANT NUMBER(s): N00014-69-A-0200-6039

9. PERFORMING ORGANIZATION NAME AND ADDRESS: Advanced Ocean Engineering Laboratory, Scripps Institution of Oceanography, P.O. Box 1529, La Jolla, Calif. 92037, (714) 452-3496

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: NR 260-105

11. CONTROLLING OFFICE NAME AND ADDRESS: Advanced Research Projects Agency, 1400 Wilson Boulevard, Arlington, Virginia 22217

12. REPORT DATE: December 31, 1974

13. NUMBER OF PAGES: 48 49

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Office of Naval Research, 800 N. Quincy Street, Arlington, Virginia 22217

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution of this document is unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Air-sea interactions
Internal waves
Ocean microstructure
Density gradient
Microstructure recorder

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This semi-annual report reflects the technical status of internal/surface wave interaction and microstructure projects conducted within the Advanced Ocean Engineering Laboratory at the Scripps Institution of Oceanography. These projects are: (1) Thermal Microstructure - to examine in detail the structure and dynamics of temperature and salinity and (2) Atmospheric Boundary Layer - to provide an understanding of the interaction between atmospheric boundary effects and surface waves.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

(49)

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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ADVANCED OCEAN ENGINEERING LABORATORY

TECHNICAL PROGRESS REPORT

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ONR Contract N00014-69-A-0200-6039

ADVANCED OCEAN ENGINEERING LABORATORY

TECHNICAL PROGRESS REPORT

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PART I. MICROPROCESSES

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PART I: MICROPROCESSES

I. PROJECT SUMMARY

During this last year one project is being completed and two major projects have been undertaken.

Past observations with free-fall microstructure recorders which sample temperature and salinity on a millimeter scale along a vertical path through parts of the ocean are being analyzed. Extensive microstructure profiles were collected by Michael Gregg at several locations in the Pacific during the past 2-1/2 years. Although he left Scripps in August 1974, he is continuing the processing of this data here with a programmer, Norio Shioura. He has made several visits to supervise the work and expects to complete the work on approximately 70 tapes by the summer of 1975. The analysis being conducted at Scripps will include the plotting, spectra, and deconvolution programs that in the past have been applied to a more limited data set.

When completed, this work promises information on the central South Pacific and the Equatorial Undercurrent in August on the North Pacific thermocline and on the mixed layer in several seasons of the year.

New analysis techniques for this data inventory will be developed by him at the University of Washington.

The two new projects are (1) development of the MSR-10, a free-falling temperature, velocity, electrical conductivity microstructure recorder, and (2) development of ship-lowered conductivity, temperature, depth (CTD) fish for documentation of temperature, salinity and density structures down to a resolution of 10 centimeters. The instruments are being developed to study the velocity and density structures, particularly at the boundaries of intrusive features in the ocean.

II. TECHNICAL REPORT

1. MSR-10

A six foot long, ten-inch diameter aluminum pressure casing was built with four wings of six foot radius, to provide rotational and falling speed stability. This instrument is

basically similar to previous ones but larger, to permit greater data collection and storage facilities, and designed for high stability and constancy of falling speed (see Figure 1), to permit measurement of velocity microstructure in addition to temperature and salinity.

In December 1974, the instrument was taken out to the San Diego Trough for extensive engineering tests. The electronic package measured the rotation rate by means of a flux-gate saturated core magnetometer (with accuracy to better than 1/2 a degree orientation to the earth's magnetic field), pressure, and the vertical and horizontal components of tilt and acceleration through two accelerometers. Figure 2 shows a record typical of the engineering drops. As can be seen from the record, the overall tilt of the instrument from the true vertical was typically not more than 0.1 degree. This represents a departure of the instrument probes at the bottom of the instrument by less than 3 mm from a plumb line to the top of the instrument. The results are in agreement with a numerical model which simulates the motion of the MSR through a shear layer in the ocean.

In addition, vertical accelerations, corresponding to changes in the falling speed, were found to be smaller than the resolution of the vertical accelerometer, or less than a change in 1 mm/sec over a 10 second time period.

These results encourage us to believe that the measurement of velocity microstructure will be possible with a sensitivity capable of detecting turbulence and shear in the very quiet ocean environment. We plan to go to sea in March of this year with a modified electronic package, already built, providing ten data channels. This first look will measure, in addition to instrumental rotation, fall rate, tilts and accelerations, the gross or overall temperature variations, and two sets of velocity and temperature microstructure probes. One set will be mounted on the nose to measure vertical temperature gradients and velocity structure, and two mounted on one of the four wings to measure the horizontal temperature and velocity microstructure. In this measurement the features of the MSR-10, namely a stable, vibrationless, free-fall platform, will be essential.

Each record from a drop will contain a continuous FM recording of the above parameters for a 100 meter vertical section, with an estimated velocity sensitivity of better than 0.1 mm/sec, and spatial resolution of about 1 mm. Since we measure the thermal microstructure in the same manner as previously, this first look will allow us to answer some important questions regarding the velocity structure of thermally active and quiet regions.

In addition to these preliminary recording techniques we are constructing a digital recording system for the MSR, incorporating a microprocessor to permit programming the instrument to examine interesting regions it encounters in far greater detail than is presently possible, in addition to allowing many more data channels. We expect to begin sea trials with this electronic package in the latter half of 1975.

2. Conductivity-Temperature-Pressure (CTD) Instrumentation for Ship Work

We have taken a CTD of Neil Brown's design to sea several times in the past year, and have obtained over 90 'yo-yo' profiles of temperature inversion regions off the San Diego coast. In each set of profiles the instrument is rapidly raised and lowered through a vertical section of about 50 m to study the details of the density structure. Emphasis has been placed on studies of intrusive features. In one study a fine structure temperature recorder was strapped to the CTD and two channels of thermal microstructure obtained for the many profiles. Analysis of this data is underway, and it appears that we can infer density gradient structures to a higher degree of sensitivity than was possible before. It has been found that the conductivity sensor (see Figure 3) on the CTD has too rapid a time response for the 0.1 second sampling interval, thus introducing unnecessary aliasing and apparent spiking in density; a new probe meeting the correct sample requirements is under construction. We plan to add two thermal microstructure channels to the CTD, and have the entire system interfaced directly with our NOVA computer system. The interface has already been built. This will allow us to make density computations and plots of data at sea, hence, facilitating adjustment of data collection depths and experimental procedures.

A joint investigation with J. Cairns and personnel at NUC, utilizing a towed thermistor chain towed at 6 knots by one ship, and our 'yo-yo' capability with the modified CTD on another ship, has been discussed, and is tentatively planned for this summer. This will provide the first detailed examination of an intrusional feature, both spatially with the towed thermistor array and temporally with our CTD, making repeated profiles of a 'tagged' region, over a period of several days.

Two papers have been completed and submitted to DEEP SEA RESEARCH and the JOURNAL OF FLUID MECHANICS. The first is a paper concerning a laboratory and numerical modelling study of

free-fall vehicle dynamids and design; the second is a report of an investigation by R.E. Lange into the behavior of the decay of turbulence in a stratified fluid. The abstracts for these two papers follow.

III. ABSTRACTS

1. "Design Considerations of Wing-Stabilized Free-Fall Vehicles", by A.C. Mortensen and R.E. Lange

This paper reports the results of a design study of a free-fall, self-rotating oceanographic instrument utilizing wings to control vertical speed and enhance stability. Numerical modelling shows this vehicle to be stable, exhibiting tilts of less than 10^{-2} radians under fall into a shear layer moving at 20 cm/sec. For non-stalled wings the fall rate, u, within possible choices of parameters consistent with a Reynolds number of ~ 50,000 is found to be expressed by

$$\frac{\omega L}{u} = \left\{ \frac{\left(\frac{1}{2}\rho u^{2} L^{2}\right)\left(\frac{C}{L}\right)}{mg} \right\}^{-.36}$$

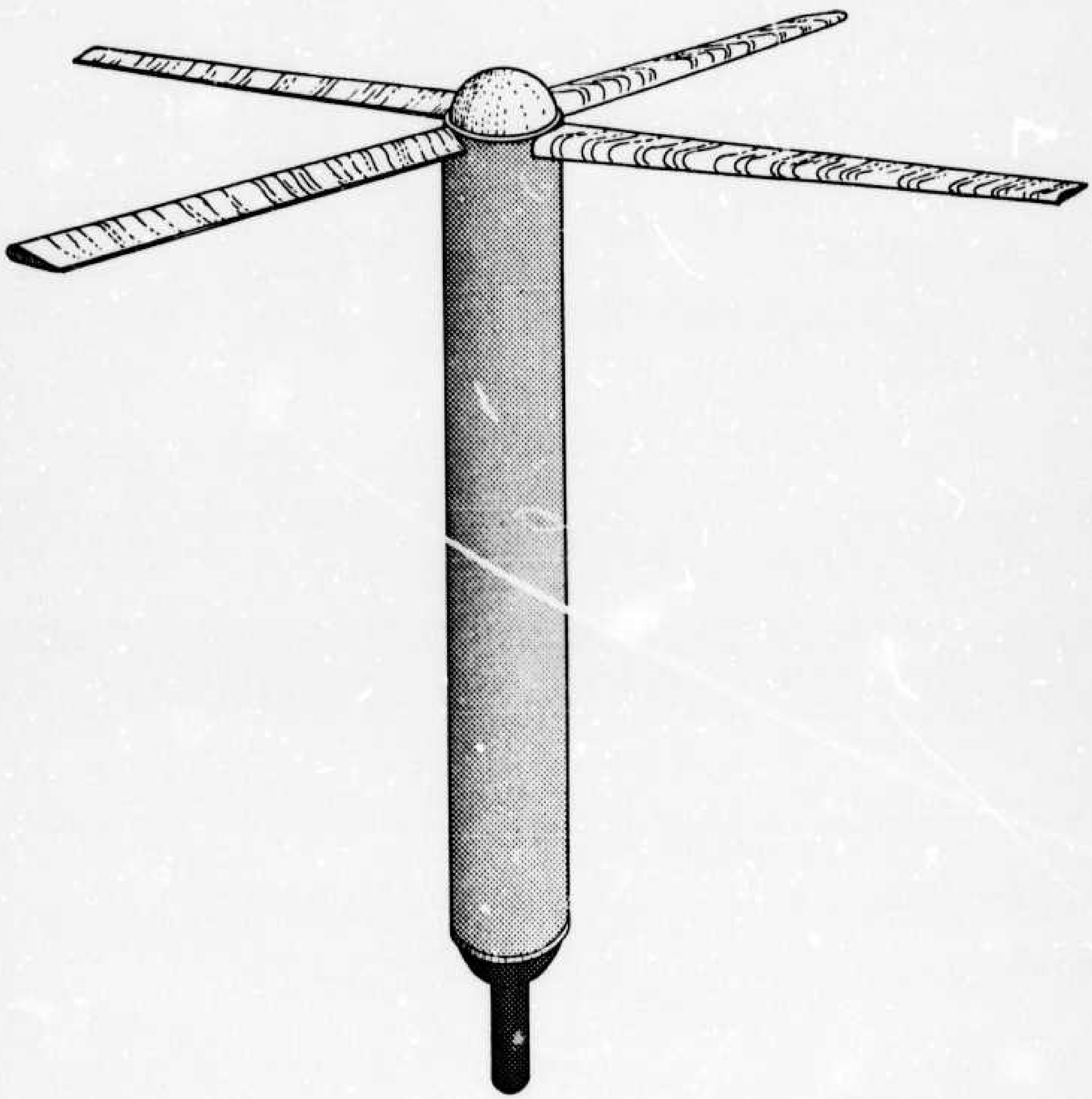
where ω = rotation rate
L = wing length
C = wing chord
mg = vehicle overweight.

With a vehicle overweight of 5 kilograms, wing length of 2 meters, and wing chord of .2 meters the calculated minimum fall velocity attainable is 8.7 cm/sec.

2. "On the Decay of Grid Generated Turbulence in Stratified Salt Water", by R.E. Lange

This is a study of the salt field in decaying turbulence in a stratified salt tank produced by towing a rectangular grid of cylindrical bars down the length of a 30 meter towing channel. The growth of the turbulent Lagrangian displacement wake in the vertical, its suppression by the stratification, and the transition to a system of layers undulating with internal waves is investigated through the use of vertically plunging electrical conductivity needle probes, and the results

scaled according to an overall Froude number U/LN, scaling the vertical wake width, where U is the grid speed, L the mesh size of the grid, and N the Väisälä-Brunt frequency of the fluid. It is found that the wake reaches a maximum vertical width at about 1/2 a Väisälä's period and scaling in vertical width proportional to the length scale (UL/N) 1/2 and then generally diminishes in vertical width until about three Väisälä's periods, when the wake is scaled by the length scale (U/N). The behavior of the variance spectra of salt fluctuations is examined in time, for different overall Froude numbers and are found to redden according to the non-dimensional decay time Nt. Finally the equipartition of energy between potential and kinetic energies is examined in one setting of U, L, N space, and equipartition is observed to hold by 1/2 a Väisälä's period, corresponding to the maximum wake growth point. A simple wake model is presented, based on the turbulence becoming suppressed when the wake reaches a characteristic Ozmidov length, and the time and vertical width values predicted by the model compared to the observed values.



MSR-10

Figure 1

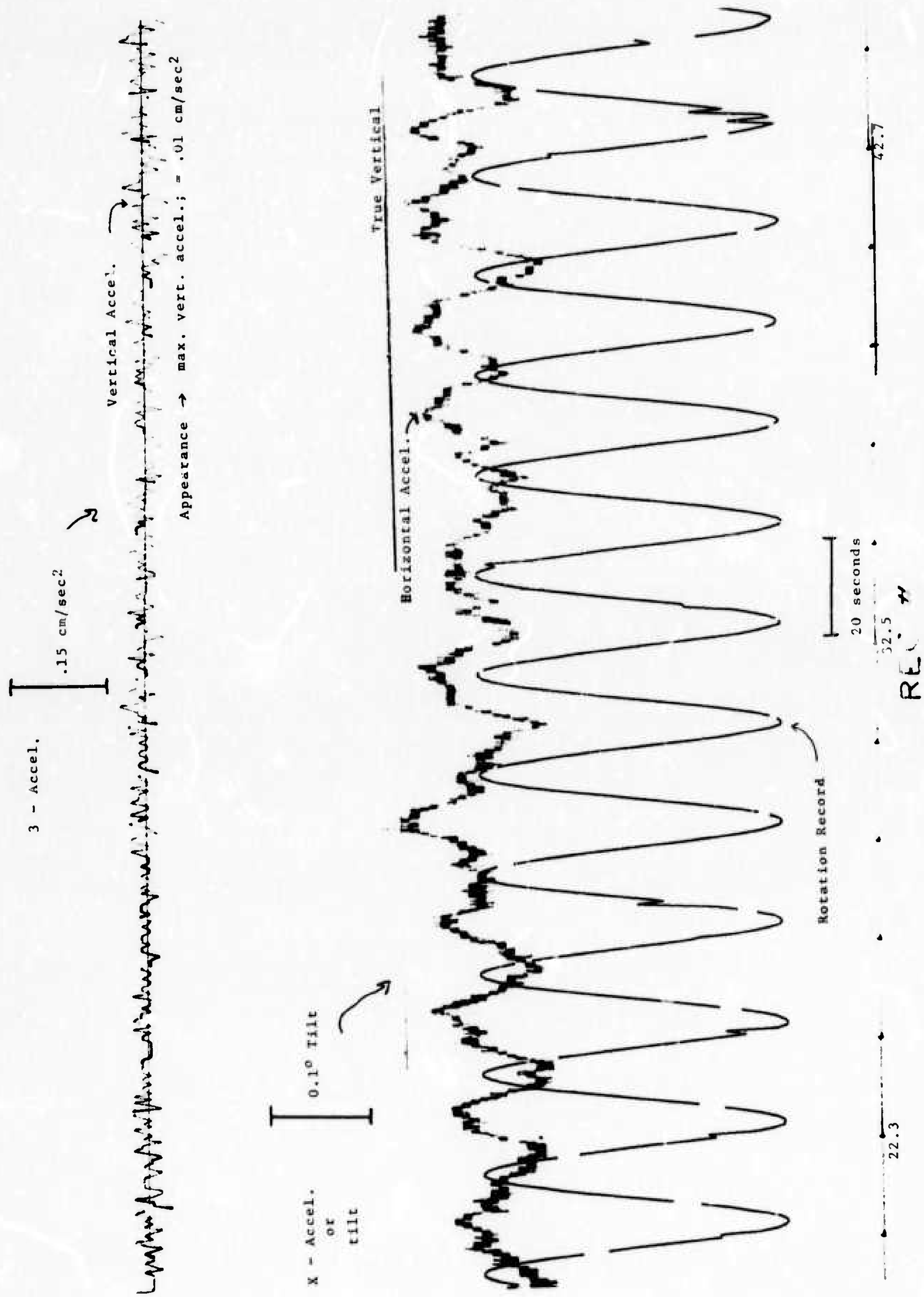
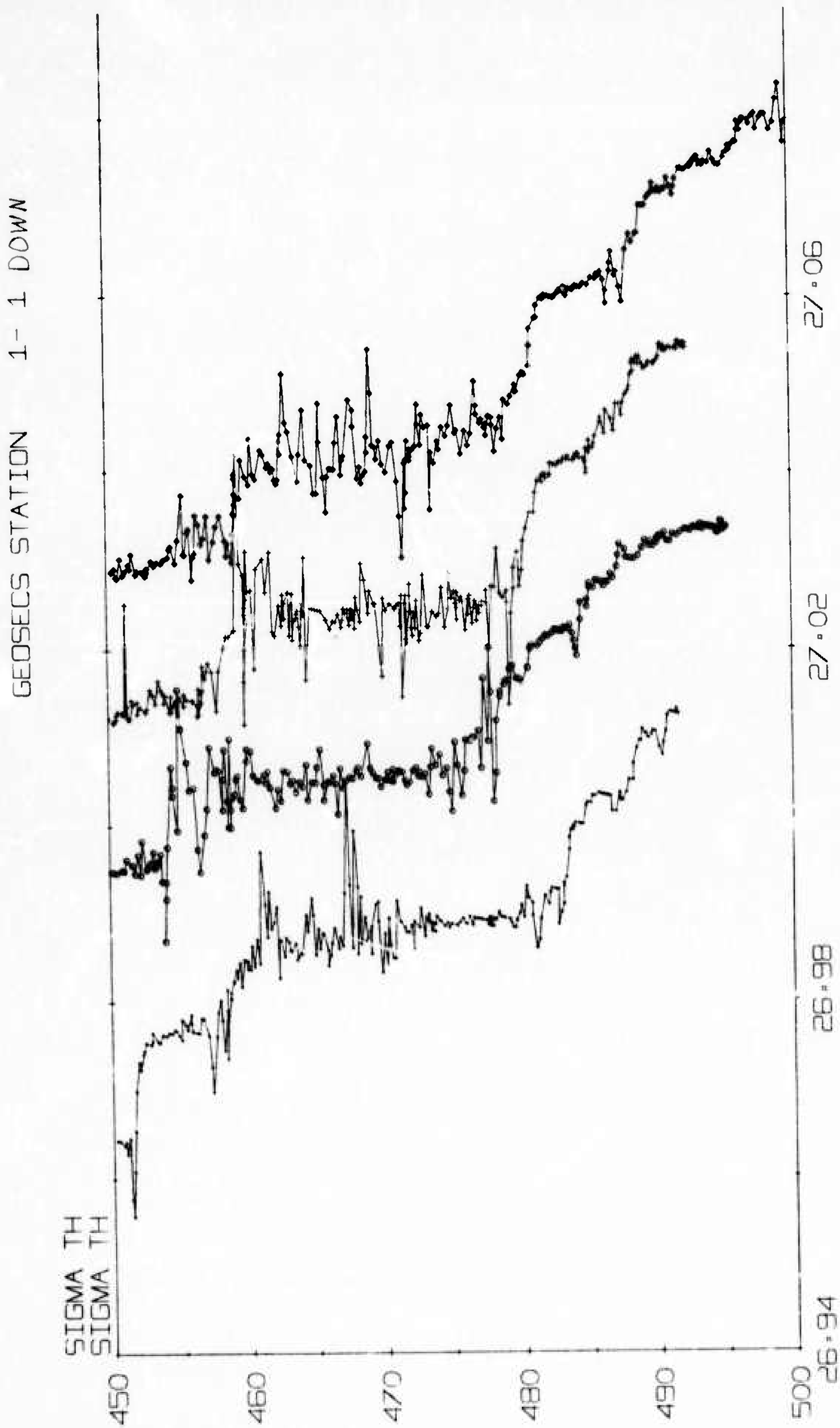

X - Accel.
or
tilt
0.1° Tilt
3 - Accel.
.15 cm/sec²
Vertical Accel.
Appearance → max. vert. accel.; = .01 cm/sec²
True Vertical
Horizontal Accel.
Rotation Record
20 seconds
22.3
32.5
42.7

Figure 2



Region of a sharp temperature inversion
(See Figure 3b)

Figure 3a

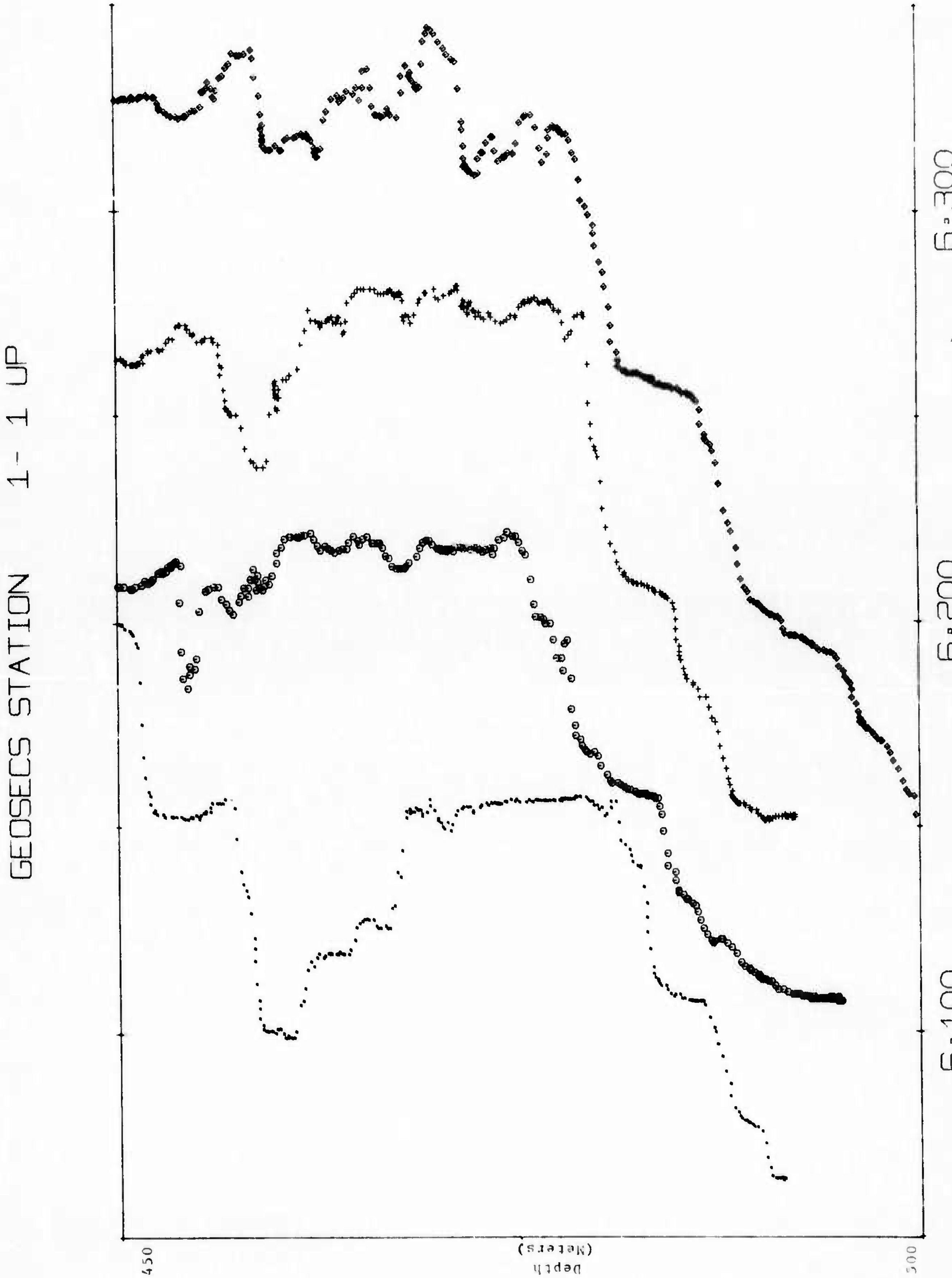


Figure 3b

PART II. MIDWATER THERMAL STRUCTURE

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PART II: MIDWATER THERMAL STRUCTURE

I. PROJECT SUMMARY

This report supplements previous reports on the development and use of a freely floating, yo-yoing midwater instrument capsule. A summary of accomplishments for the period July 1, 1974 - December 31, 1974 is given.

II. TECHNICAL REPORT

1. Internal Waves

During June - July 1974, internal wave records of 21 days duration were obtained at a depth of 350 m in an area 500 miles southwest of San Diego. The analysis of these data is nearly completed. The resulting vertical displacement spectra decrease generally as ω^{-2} between the local inertial frequency (ω_i) and the Brunt - Väisälä frequency (N), and drop sharply outside these limits. Just below N there is a pronounced spectral peak. Vertical coherences measured over separations up to 100 m are nearly independent of frequency between ω_i and N. Within the range $0 < \omega < .5N$ coherence decreases linearly with vertical separation. Phase spectra indicate equal upward and downward transport of wave energy. An internal wave model proposed by Garrett and Munk is in general agreement with these observations. Both the displacement and coherence spectra suggest that internal wave energy is concentrated primarily in the first few vertical modes. These results will be submitted for journal publication in the second quarter of 1975.

No internal wave measurements are scheduled for the immediate future. However, as a prelude to water motion studies planned tentatively for 1977, the study of capsule dynamics is continuing. In early spring of 1975 the behavior of the capsule in an unstratified fluid (Lake Tahoe) will be examined. Then again in fall of 1975, its dynamics in a thermally stratified lake will be studied.

By understanding the capsule dynamics we hope in later experiments to be able to infer water motions from the corresponding motion of the capsule.

2. Ocean Microstructure

Analysis of the June 1973 microstructure data has been completed. Results are reported in Williams (1975), the abstract of which follows:

> A freely drifting, midwater float has been developed and used to obtain profiles of temperature gradient (≈ .02 m resolution) and temperature (~.5 m resolution) at ~6 min intervals. Twenty hours of data obtained at 550 m depth 500 km offshore from Southern California are analyzed for thermal structure and internal wave motions. Intense microstructure activity is episodic. Three microstructure lenses, one of which is bimodal, are found: two are associated with small intrusions of ~5 m vertical extent and ≤100 m horizontal extent in the horizontal direction of sensor motion. The third lens is interpreted as being the result of a shear instability. The Cox number is ~1.5 orders of magnitude greater for profiles containing inversions than elsewhere. Two microstructure lenses are associated with internal wave shear maxima, the third is associated with a shear minimum. This result hints at a possible relation between internal wave shear and microstructure activity.

A journal article to more widely disseminate these results is near completion.

In early 1975 additional microstructure measurements are planned in a deep, fresh water lake, a setting in which salinity effects on the density stratification are minimal. Ocean measurements are planned for later in the year with salinity sensors augmenting the present sensor complement. The added sensors will reduce ambiguities present in temperature data alone.

III. REFERENCES

Williams, G.O. (1975) Microstructure and Internal Wave Measurements from a Midwater Float. Ph.D. Dissertation, University of California, San Diego.

PART III. SURFACE WAVES AND NEAR SURFACE EFFECTS

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PART III: SURFACE WAVES AND NEAR SURFACE EFFECTS

I. TECHNICAL REPORT

Work has continued in the analysis of air sea interaction measurements taken during the ARPA sponsored OWAX cruise of FLIP in 1973.

Comparison of direct and indirect measurements of fluxes of momentum sensible heat and latent heat were carried out by Dr. Gregory Dreyer in his Ph.D. dissertation[1] and will be the subject of forthcoming publications. Major platform motion corrections were carried out successfully for the first time so that the effect of this error on the direct covariance estimate could be determined. It was found that tilting motions of FLIP cause errors as high as 30% in the direct measured momentum flux, but are negligible for latent and sensible heat fluxes.

Analysis of high frequency response temperature sensor signals taken during OWAX by Steve McConnell show significant departures from universal similarity spectra forms for high Reynolds number scalar fields with corresponding Prandtl number. A summary report was given at the APS Fluid Dynamics Division meeting in Pasadena in November 1974[2]. It was found that for unstable conditions in the marine boundary layer the temperature spectra exhibit power law behavior less "steep" than the expected $f^{-5/3}$ inertial subrange expected - sometimes approaching $\sim f^{-4/3}$. Inertial subrange constants evaluated when $f^{-5/3}$ spectra appeared were quite variable and generally large, as though a high frequency mode of dissipation were present. McConnell observed an apparent correlation with absolute humidity for about eight different runs in four expeditions, and suggested a possible explanation might be radiative damping. A conclusive explanation for the large departure of over ocean temperature spectra from $f^{-5/3}$ is still forthcoming, but seems to be associated with a "cold spike" signature in the temperature signal at the interface of a large scale roll-like structure over the open ocean during unstable conditions. "Cold spikes" appear to be due to some sort of evaporative phenomenon - but the precise mechanism is not understood at this time, and is under active investigation. Simultaneous measurements of the water vapor concentration showed no anomalous behavior as found for the temperature. Further discussion of this phenomena is included in Dreyer's dissertation and in Friehe et al (attached)[3].

II. FUTURE WORK

Support for this work has been terminated by ARPA.

II. REFERENCES

1. Dreyer, Gregory F., Ph.D. Dissertation, "Comparison of Momentum, Sensible and Latent Heat Fluxes Over the Open Ocean Determined by the Direct Covariance, Inertial and Direct Dissipation Techniques", University of California, San Diego, 1974.

2. McConnell, Steve and Carl H. Gibson, "Temperature Derivative Spectra Over the Open Ocean", Abstract submitted to APS Twenty-Seventh Annual Meeting November 1974, Pasadena, California.

3. Friehe, Carl A., C.H. Gibson, F.H. Champagne and J.C. LaRue, "Turbulence Measurements in the Marine Boundary Layer", Atmospheric Technology, 1974.

Attachment 1

Turbulence Measurements in the Marine Boundary Layer

by

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F.H. Champagne and J.C. LaRue

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1. Introduction

As approximately three-quarters of the earth's surface is covered by water, about three-quarters of the atmospheric boundary is over a water surface. The transfer rates of momentum, heat and moisture through the marine boundary layer have large effects on the global weather system, oceanic and atmospheric circulations and heat contents and their interactions. However, more effort has been expended in the past on atmospheric measurements over land than over the seas. Recently (since about 1968) extensive and detailed measurements have been made in the marine boundary layer. It is our purpose here to describe the methods used and measurements obtained by our research efforts in the marine boundary layer in the last few years.

The marine boundary layer is characterized by turbulent, rather than laminar, motion. Therefore, in making measurements in the marine boundary layer, one is making measurements of the turbulent velocity field and associated fields of temperature and water vapor content that are mixed by the turbulent motion. In order to measure velocity, temperature and water vapor, instrumentation of high sensitivity and bandwidth is required to measure the entire spectrum of the turbulent signals. For example, the energy of the vertical component of the turbulent velocity vector is typically concentrated at about 0.01 to 0.1 Hz, and is dissipated by viscosity at between 100 to 1000 Hz for the range of usual marine boundary layer conditions. Thus to measure the entire bandwidth of the signal requires sensor (and recording and associated instrumentation) bandwidth from essentially d.c. to about 1 kHz. Signal to noise requirements are also large,

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*Also Scripps Institution of Oceanography

since the power spectra of most of the signals have a fairly rapid roll-off; in the inertial subrange power spectrum is proportional to frequency to the -5/3 power. The above remarks apply to measurements over land as well as over the oceans. Ocean measurements are further complicated by additional factors, such as typically lower signal levels, a more severe environment, and difficulty in obtaining measurements that are not affected by wave-induced motion of the ship or instrument platform. Also, over land the measurement of moisture is not often made, or measurements are made in areas or under conditions under which moisture is not important. Over the oceans, moisture is obviously important, but a difficult variable to measure.

In summary, measurements in the marine boundary layer provide information about the exchange of heat, moisture and momentum between the oceans and atmosphere. These, together with radiation and precipitation measurements, will further our understanding of weather, oceanic processes and their interactions. Also, the marine boundary layer is a "laboratory" for fundamental turbulence measurements. Most turbulence theories apply at large Reynolds numbers (the Reynolds number is the ratio of inertial to viscous forces in fluid motion), and in the atmospheric boundary layer the Reynolds numbers are typically several orders of magnitude greater than that obtainable in laboratory flows. The scales of the motion are also large so that sensor sizes are at least feasible to manufacture to resolve the smallest scales in the flow field.

2. Measurement Facility: FLIP

Measurements of atmospheric turbulence over the open ocean have been made from at least four types of platforms: moving ships (Mitsuta, et al (1974)), a gyro-stabilized buoy (Dunckel, et al (1974)), a aircraft (Miyake, et al (1970)), and from the manned spar buoy R/P FLIP* (Pond, et al (1971), Gibson et al (1970), for example). In this article we will review primarily measurements made from FLIP. FLIP, as configured for a recent atmospheric experiment, is shown in Figure 1. About 100 m of FLIP is underwater so that surface wave generated pressures have little effect on FLIP's vertical motion. (For more detailed information on the design and performance of FLIP, see Rudnick (1967)). Atmospheric

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*FLIP - Floating Instrument Platform, operated by Scripps Institution of Oceanography

sensors are placed at the end of the large port boom to avoid, as much as possible, effects due to the distortion of the wind field around FLIP. The starboard boom has a sail on it to balance the drag of the larger boom so that FLIP's keel is kept pointing into the wind. (In Figure 1, the wind would be coming out of the picture toward the reader.) Sensors are located on small masts above boom level, or below to obtain measurements near the surface (not shown in Figure 1). Some measurements at about 30 m above the mean ocean surface have also been made from a collapsible vertical mast (shown lowered in Figure 1). Signal cables are strung from the sensors to the laboratory, located at the level of the booms. About 12 "bays" of electronic instrumentation can be placed in the laboratory, and about 10 scientists can be accommodated for a maximum single period of 30 days.

The motion of FLIP is of course much less than the motion of a regular surface ship. However, the residual motion does contaminate some measurements, especially that of the vertical velocity component. Our method of correcting for this motion is described later.

3. Experimental Methods

3.1 Instrumentation

a. Velocity

Three independent devices are generally used to measure the wind velocity. A standard micrometeorological cup anemometer is used to record the horizontal wind speed and fluctuations up to about 0.5 Hz. A three-dimensional sonic anemometer is used to measure simultaneously the three components of the velocity vector from d.c. to 10 Hz. The cup and sonic anemometers do not require calibration in the field, but are tested in the UCSD AMES low speed wind tunnel to verify operation before and after field trips. For high frequency velocity component measurements, linearized constant temperature anemometers are used with hot-wire or hot-film single or double sensor probes. The double sensor probes are in an "X" configuration for the measurement of the horizontal and vertical velocity components. Bandwidth is typically d.c. to several kHz with probe cables 50 m long. The probes are calibrated in a small variable speed, controlled air temperature wind tunnel inside the laboratory on FLIP before and after use, without disconnecting the probes from the anemometer circuitry.

By this technique, we have found that the cylindrical hot-film sensors (0.025 mm diameter, 0.5 mm length) hold calibration in the marine atmosphere better than hot-wire sensors (0.0038 mm diameter, 1.2 mm length). (See also Davidson (1974)). The calibration tunnel facility is also equipped with a protractor (0.1 degree resolution) for direct angular calibration of the X probes.

b. Temperature

Measurements of the full dynamic range of fluctuating temperature signals in the marine boundary layer are not routine. The signal level is usually quite low, 0.1C (root-mean-square) or less, over a bandwidth of ~ 10^{-3} to 10^{3} Hz. Thermocouples and thermistors do not have adequate frequency response characteristics to measure the entire spectrum of the temperature signal. Extremely fine platinum wire sensors (0.625 μ* diameter, 0.2 mm length) have to be used to obtain adequate frequency response (approximately 1.5 kHz) required to measure the full bandwidth of the signal, and to resolve the smallest significant scales in the flow, about 1 mm. The typical resistance of a 0.625 μ Pt sensor is a few hundred ohms, and is operated in a low-noise, transformer-coupled a.c. Wheatstone bridge. The battery-powered a.c. bridge is placed near the sensor so that only a few feet of interconnecting probe cable is required in order to avoid excessive capacitance problems and noise pick-up. The current through the sensor is kept small, usually 250 microamperes, to reduce self-heating of the sensor and subsequent velocity sensitivity. In situ calibration is obtained by electronically switching a calibrating resistor in parallel with the sensor of such a value that the resulting change in the output signal corresponds to a 1 degree C change in temperature. The noise level measured in the laboratory is about 4×10^{-10} C^2/Hz, only two times the theoretical Johnson noise level.

For some measurements of the fine scale features of the turbulent velocity-temperature field, a Pt "cold" wire as described above is placed less than 1 mm from a hot-wire sensor. Such probes have been fabricated in the laboratory on FLIP by J. Clay and S. McConnell. Mean absolute temperature measurements are made with quartz thermometer probes or commercial platinum resistance probes, radiation shielded and aspirated. Bulk sea temperature has been obtained from a quartz thermometer probe suspended about 1 m below a tethered surface float.

*μ = micron = 10^{-6}m.

c. Water Vapor

Measurement of the fluctuations of water vapor content with spatial and temporal resolution equal to that for velocity and temperature fluctuations is not possible with existing instrumentation. Wetted thermocouples or thermistors have slow response times, and the psychrometric relationship has to be used to obtain measurements of water vapor density (absolute humidity, $\mu gm/cm^3$). We have chosen to use the Lyman-alpha humidiometer, which directly measures water vapor density in the atmosphere. (See A. Buck (1973), for a detailed description of this instrument.) The instrument measures the absorption of the Lyman-alpha line of hydrogen, which is assumed to be caused only by the hydrogen contained in water vapor in the measuring path. The absorption approximately follows Beer's law, so that an exponential dependence of detector tube current on water vapor concentration is obtained. The output is often linearized with a logarithmic amplifier. The commercial instrument has hydrogen source tubes and nitrous oxide detector tubes of about 2 cm in diameter and 5-8 cm long. The path length is adjustable from about 0.5 cm to 5 cm. Thus the spatial resolution is not adequate to measure the "dissipative" scales of the fluctuating water vapor field, of the order of 1 mm. A further operational problem with the Lyman-alpha device is that the tube windows are of magnesium flouride, which transmit the Lyman-alpha line 1216 A), but are slightly soluble in water. Attenuation of the signal occurs due to deterioration of the windows from spray or exposure during squalls. Unfortunately, a better window material has not been found.

To measure average and low frequency water vapor content and to calibrate in situ the Lyman-alpha humidiometer, a "cooled mirror" dew point instrument is used. This device has a dew point accuracy of about 0.3 C (about 0.2 $\mu gm/cm^3$). The basic principle of operation is the measurement of the temperature of a metal membrane that is heated or cooled until dew is formed on the surface.

d. Motion

Slight motion of the FLIP affects primarily the measurement of the instantaneous vertical velocity component. The outputs of the sonic and X-probe anemometers are the same for an actual variation of the turbulent velocity vector or an equivalent motion of the sensors in a uniform flow. Since the horizontal velocity component is typically an order of magnitude greater than the vertical component, small tilting angles about the vertical axes of the sensors can cause

appreciable contamination of the vertical velocity component by the horizontal component. Also, there are true velocity effects in the measured signals due to the fact that FLIP is usually slowly moving with respect to a fixed reference frame. To correct the first effect of tilt sensitivity of the anemometer sensors, a vertical gyroscope (originally obtained by R. Davis of SIO) is placed next to the sensors to measure the instantaneous tilt angle. The tilt correction is performed on the data by digital analysis in the (land) laboratory. The total motion of FLIP is in general complicated, since there are three components of angular motion and three of translational motion. An airline inertial navigation unit (very similar to the one used on the NCAR Electra) has been used once to measure the six components, and the data is presently being reduced.

3.2 Instrumentation Package

The total instrument package is shown in Figure 2, with the exception of the dew point/mean air temperature unit. The mounting frame is quite rigid and the angles between the gyroscope and anemometer sensor mounting pads are precisely set in the laboratory. The gyroscope is calibrated on a special tilt table in the (land) laboratory with respect to the vertical.

3.3 Signal Processing and Recording

Data are recorded on FLIP mainly on analog FM instrumentation magnetic tape recorders. Many channels (up to 20), several of high bandwidth, must be recorded simultaneously. The information rate is too large for practical digital recording, although in some experiments we have used a on-line minicomputer system which stores data on digital tape.

Since the root-mean-square signal to noise ratio of FM recorders is only about 50 dB, pre-processing of the basic signals is required before recording to preserve their full dynamic ranges, which may exceed 50 dB. Signal processing equipment consists of precision d.c. offset and gain amplifiers, analog filters, differentiators and pre-emphasis circuits (of a specially shaped transfer function to pre-whiten typical atmospheric turbulent velocity and temperature spectra). Time division multiplexing is used to record low frequency information from several (up to 7) instruments on one analog tape track. Observational

equipment used on board FLIP to monitor signal quality includes usual storage oscilloscopes and strip chart recorders, and a power spectrum analyzer. As mentioned above, a minicomputer has been used to collect data, and also perform in situ data checks.

3.4 Digital Analysis

The recorded data is converted to digital form in the laboratory at UCSD (Gibson (1973)). Two computer systems are used for various statistical and spectral analyses; IBM 1130 and TI 980 in the laboratory or the University CDC 3600. Digitization for the 1130 and 980 are 14 bit with sampling rates up to 8 kHz per channel; for the 3600, 12 bits are used. Four channels of matched 48 dB/octave analog low pass filters are available to minimize aliasing for spectral analysis. Spectral analysis is done using fast Fourier transform routines.

4. Results and Discussion

A typical time series trace of horizontal and vertical components of the velocity vector, temperature and humidity fluctuations is shown in Figure 3. The data were obtained from FLIP at a height of about 10 m over the water under conditions of relatively cold, dry air over hot (wet) water. The fluxes of momentum, heat and water vapor can be directly calculated from the time series. The vertical flux of momentum is proportional to the covariance of the horizontal and vertical velocity components; the vertical flux of sensible heat is proportional to the covariance of the fluctuating temperature and vertical velocity; and the vertical flux of moisture is proportional to the covariance of the fluctuating water vapor concentration and the vertical velocity. The evaporation of water at the air-sea interface represents a latent heat loss from the ocean. For the conditions described above, the covariance of the two velocity components is negative, while the covariances of the vertical velocity component with the scalar fields are positive. The signs of the covariances are somewhat difficult to determine by inspection of the time series plots since the correlation coefficients (absolute value) are usually less than one-half. There is a fairly high correlation between the temperature and humidity fluctuations, and the time trace exhibits a characteristic ramp structure of slowly increasing temperature and humidity with time, leading to a sharp interface. The correlation of temperature and humidity is not always perfect: at some of the ramp interfaces the temperature decreases to

abnormally low values ("cold spikes") compared to the behavior of the humidity. An example of such a time series is shown in Figure 4. The anomalous "cold spikes" of the temperature field were apparently first observed in project BOMEX (Pond, et al (1971)). Hypotheses advanced to explain the "cold spikes" include radiative effects and mixing of upper-level air of different temperature and humidity profiles (Pond et al (1971)), and evaporation of spray at the ramp interfaces (Dreyer (1974)). There have not been reports of "cold spikes" in temperature fields observed over land.

Spectral analysis has been of great importance in understanding the physics of turbulent motion and mixing of scalar fields by turbulence. The similarity hypotheses and inertial subrange prediction of Kolmogorov should be particularly applicable to the high Reynolds number turbulent atmospheric boundary layer. Power spectra of velocity components, temperature fluctuations and humidity fluctuations from low ($\tilde{}10^{-3}$Hz) to moderate ($\tilde{}10$ Hz) frequencies obtained from FLIP are shown in Figures 5a and 5b. The velocity data were obtained with a sonic anemometer, and show an approach with increasing frequency to the Kolmogorov inertial subrange form of spectral energy proportional to the -5/3 power of frequency. (The Kolmogorov inertial subrange form is expressed in wave number; the conversion from frequency is made by equating the streamwise spatial coordinate to the product of time and the mean velocity past the fixed measuring probe.) The humidity fluctuation data obtained with the Lyman-alpha device also shows an inertial subrange behavior for scalars, as predicted by the Obukhov-Corrsin analyses similar to Kolmogorov's for the velocity field. However, the temperature fluctuations do not exhibit an inertial subrange. The slopes of the temperature power spectra for the marine boundary layer are consistently less than -5/3 over a wide frequency range, apparently largely due to the "cold spikes". The basic reason (or reasons) for this behavior are not fully understood. To a first approximation, temperature and water vapor content should behave as identical passive scalars. The molecular diffusivity of heat in air is within 20% of that of water vapor in air, and the governing equations are the same, except for source or sink terms due to radiative effects and evaporation of spray.

High frequency, fine scale results for the velocity and temperature fields are presented as power spectra of the time derivatives of the variables. The frequency dependence in the inertial subrange for the power spectrum of a derivative becomes $f^{-5/3} \cdot f^2 = f^{1/3}$, where f=frequency. As shown in Figure 6, the velocity power spectrum exhibits the $f^{1/3}$ form, whereas the temperature derivative obtained at three heights

does not, except for a small region of tangency before the diffusive roll-off. To confirm the departure of the over ocean temperature results from the inertial subrange form, derivative power spectra were obtained in a laboratory flow at moderately high Reynolds number - a heated turbulent jet (so large that the experiment had to be performed in the UCSD gymnasium). Essentially the same equipment for the field experiments was used, and both the temperature and velocity derivative spectra substantially followed the inertial subrange form indicating that anomalous instrument response was not a factor. It has also been determined that the fine scale structure is not isotropic, as evidenced by non-zero values of the skewness of the time derivatives of temperature in the marine boundary layer as found by Gibson, et al (1970) and Boston and Burling (1972). The "universal" constant associated with the dimensionless form of the inertial subrange formula for temperature was found in those two studies to be greater (by factors of 2 to 3) than values measured in previous laboratory studies.

5. Conclusions

Turbulence measurements in the marine boundary layer provide insight into the physical mechanisms of air-sea interaction and high Reynolds number turbulence. Measurements of the fluxes of momentum, sensible heat and water vapor over the oceans are required to further our understanding and modeling of atmospheric and oceanic processes. Direct flux measurements (calculating the appropriate covariances of the turbulent signals) are essential to confirm or calibrate other indirect, simpler techniques. Such efforts are conveniently performed from a stable platform such as the FLIP. The simplest indirect flux estimate method is the use of the bulk aerodynamic formulas (Roll (1964)) which relate the fluxes to observations of mean air and sea temperatures, mean water vapor concentration, and mean wind speed. The empirical coefficients in the formulas are determined experimentally by comparison to simultaneous direct flux measurements, as by Pond et al (1971), for example. Another technique involves fine scale measurements of the dissipation rates of velocity and temperature fluctuations (the dissipation rates are proportional to the variances of the time derivatives of the fluctuations). From the measured rates, the momentum and sensible heat fluxes may be inferred (Stegen, et al (1973)). The simpler techniques are of interest as they do not involve measurement of the vertical velocity component, and therefore may work on conventional ships.

Fine scale measurements in the marine boundary layer have revealed some departures from theoretical predictions and assumptions about turbulence at high Reynolds number, particularly for the temperature field. The reasons for the departures are not presently understood and are an active subject of present research.

ACKNOWLEDGMENTS

We would like to acknowledge the efforts of J. Clay, G. Dreyer, and S. McConnell who participated in several field experiments, and from whose work some of the present results were obtained.

T.K. Deaton has designed and fabricated a large portion of our instrumentation and participated in the field experiments. The crew of the FLIP have been most helpful in the field experiments, especially Dewitt Efird, presently officer-in-charge. Support for this research has been obtained from the National Science Foundation (Atmospheric Sciences Section) Grant GA-28366, Office of Naval Research Contract N00014-69-A-0200-6049, and the Advanced Research Projects Agency, monitored by Office of Naval Research under Contract N00014-69-A-0200-6039. One of us (C.A.F.) received support from Project NORPAX (jointly sponsored by the National Science Foundation and Office of Naval Research) during the preparation of this article.

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Figure 1a and 1b: FLIP, "flipped" and being rigged for marine boundary layer measurements. FLIP is towed, in the horizontal position, to and from the experimental site as in Figure 1b. FLIP does not have any propulsion power of her own, is properly called a spar buoy. Transition from the horizontal to the vertical takes about 30 minutes; from vertical to horizontal about 15 minutes. The side booms are folded for the horizontal position. Electronic instrumentation is mounted sideways in standard racks in the laboratory in the horizontal position. Transfer of scientists and small equipment to support vessels is possible by use of the small boat.

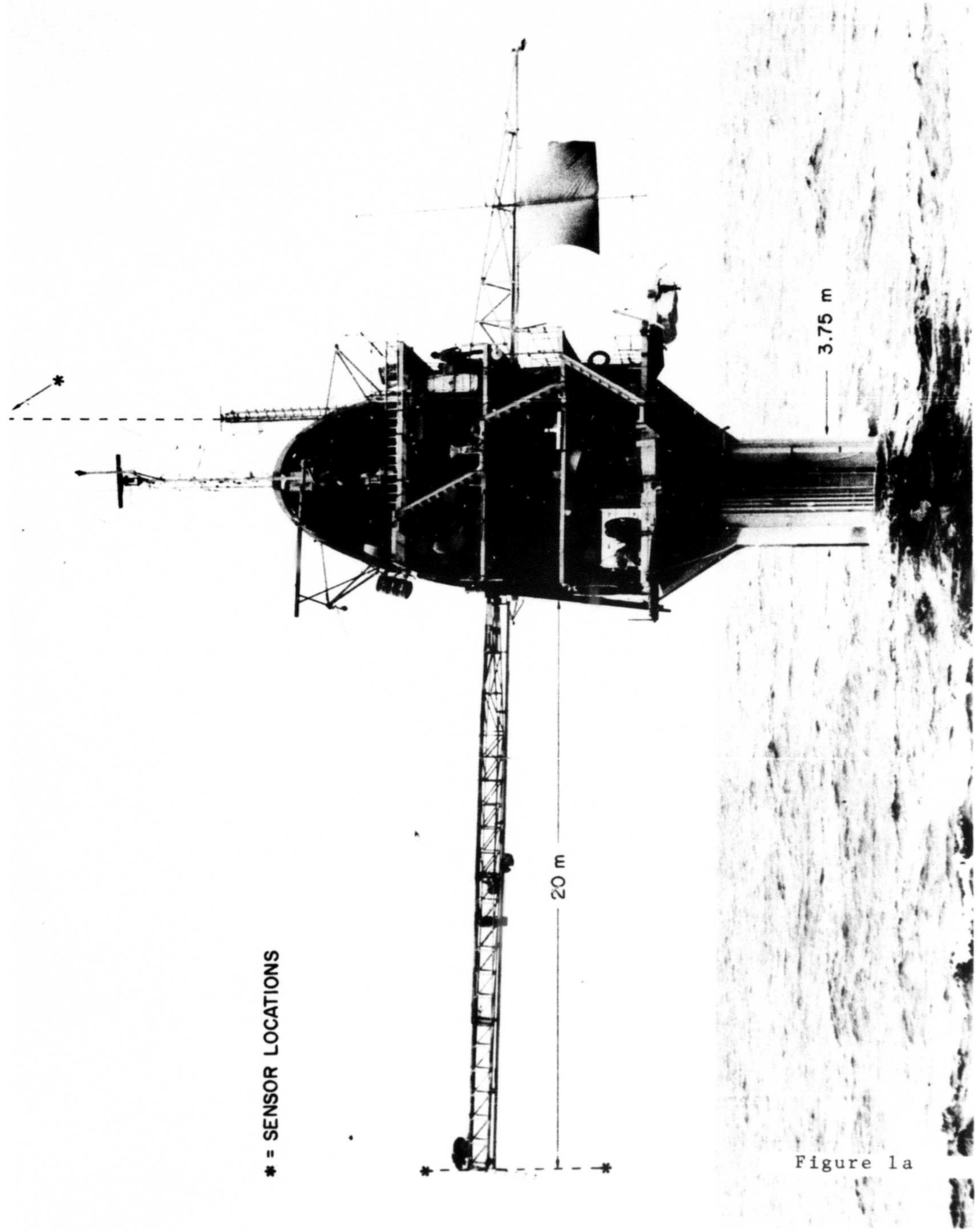


Figure 1a

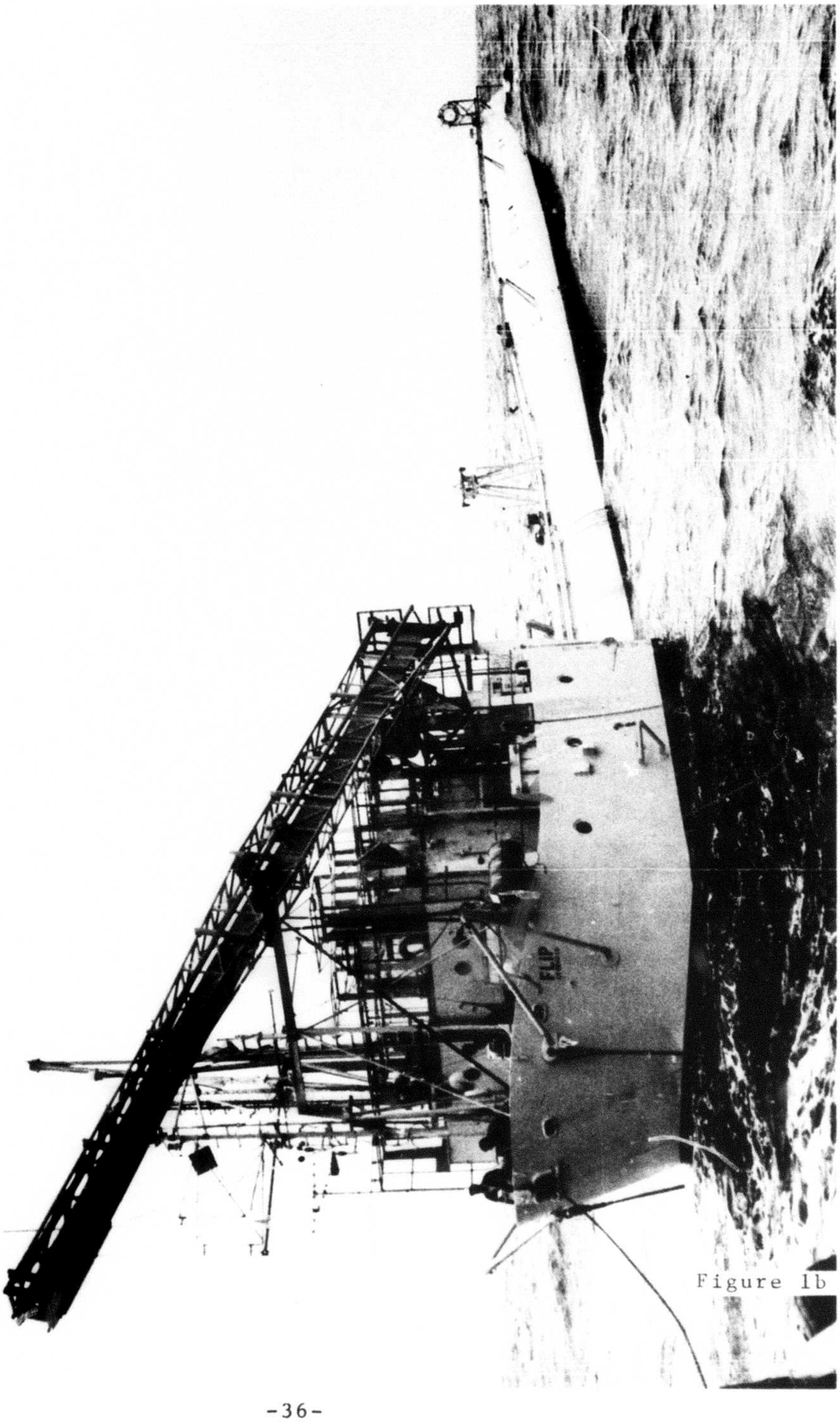


Figure 1b

Figure 2a: Turbulence and micrometeorological instrument package. A. Velocity sensors: (1) Three-dimensional sonic anemometer, (2) Hot-wire/film velocity probe (single or X-sensors) for use with constant temperature anemometers, (3) Cup anemometer. B. Temperature sensors: (4) Platinum wire temperature sensor probe for use with the a.c. bridge circuit, (5) Thermistor probe. C. Water vapor sensors: (6) Lyman-Alpha humidiometer. (Not shown is mean air temperature and dew point instrument). D. Motion sensor: (7) Vertical gyroscope.

Figure 2b: Front view.

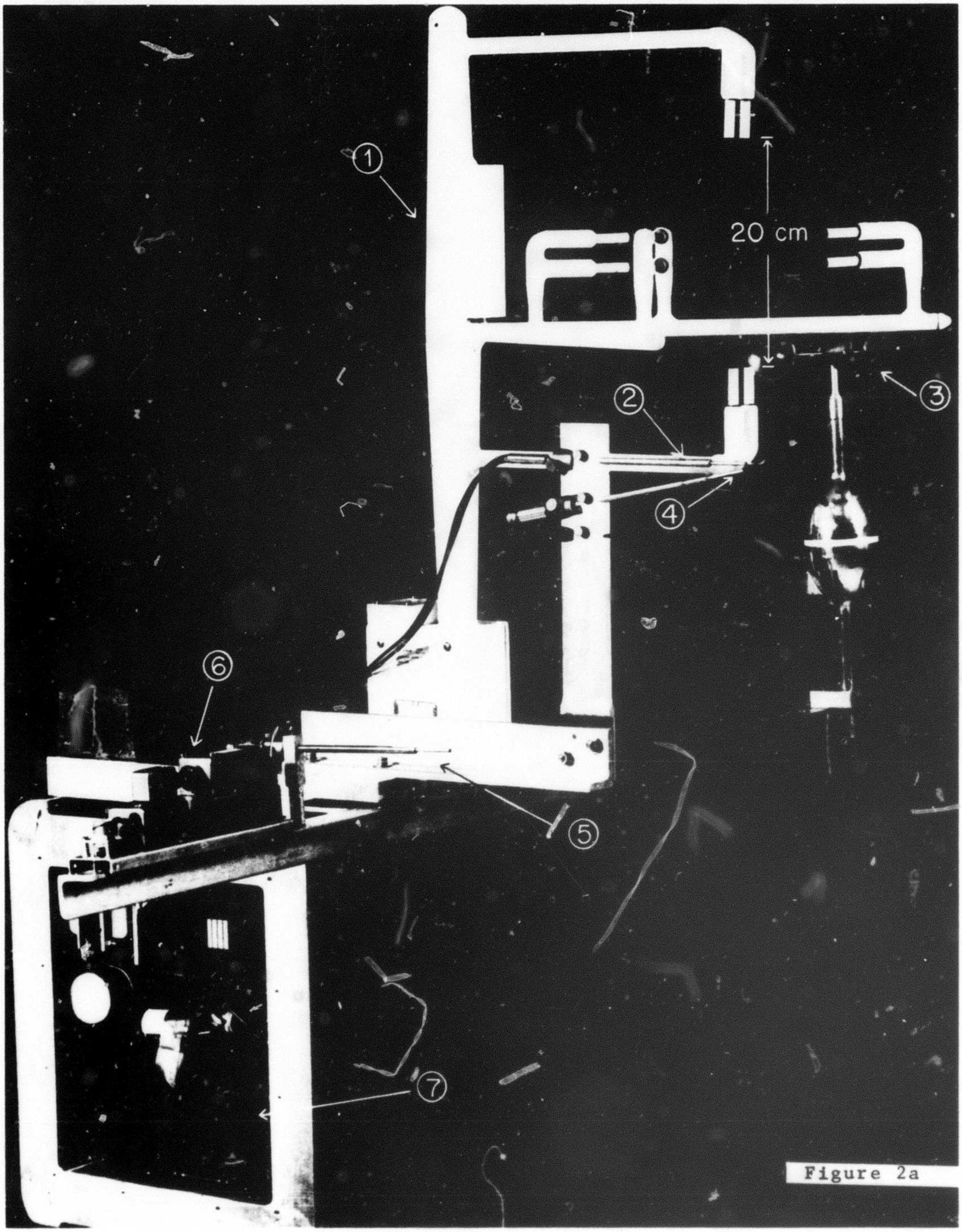


Figure 2a

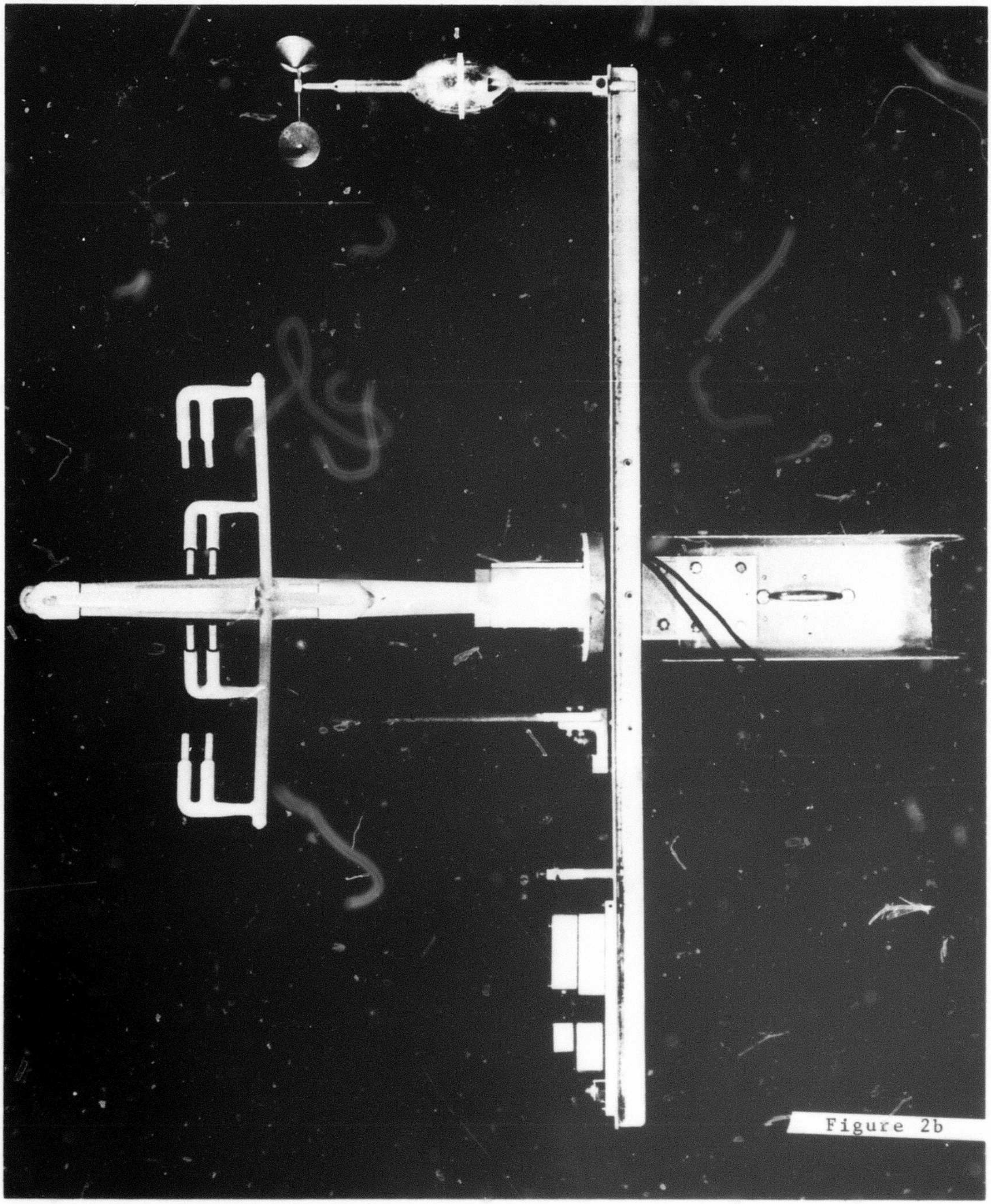
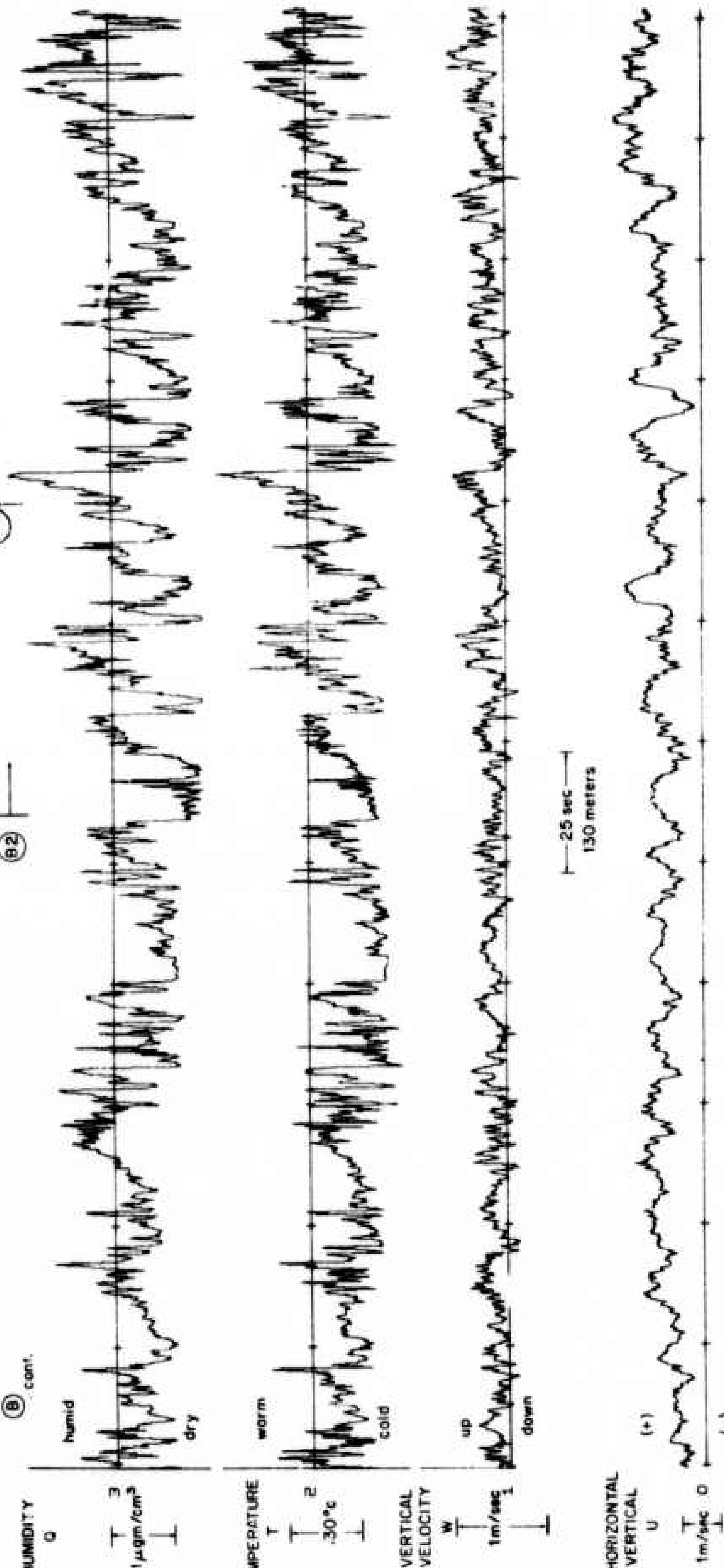


Figure 2b

Figure 3: Time series of horizontal and vertical velocity components, temperature and humidity. The vertical flux of sensible heat is proportional to the covariance of the temperature and vertical velocity time series; the vertical flux of moisture is the covariance of the absolute humidity and the vertical velocity; the vertical flux of momentum is proportional to the covariance of the horizontal and vertical velocity components.


B cont.
B2
B22
HUMIDITY
Q
3
1 μgm/cm³
humid
dry
TEMPERATURE
T
2
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cold
VERTICAL
VELOCITY
W
1m/sec
1
up
down
HORIZONTAL
VERTICAL
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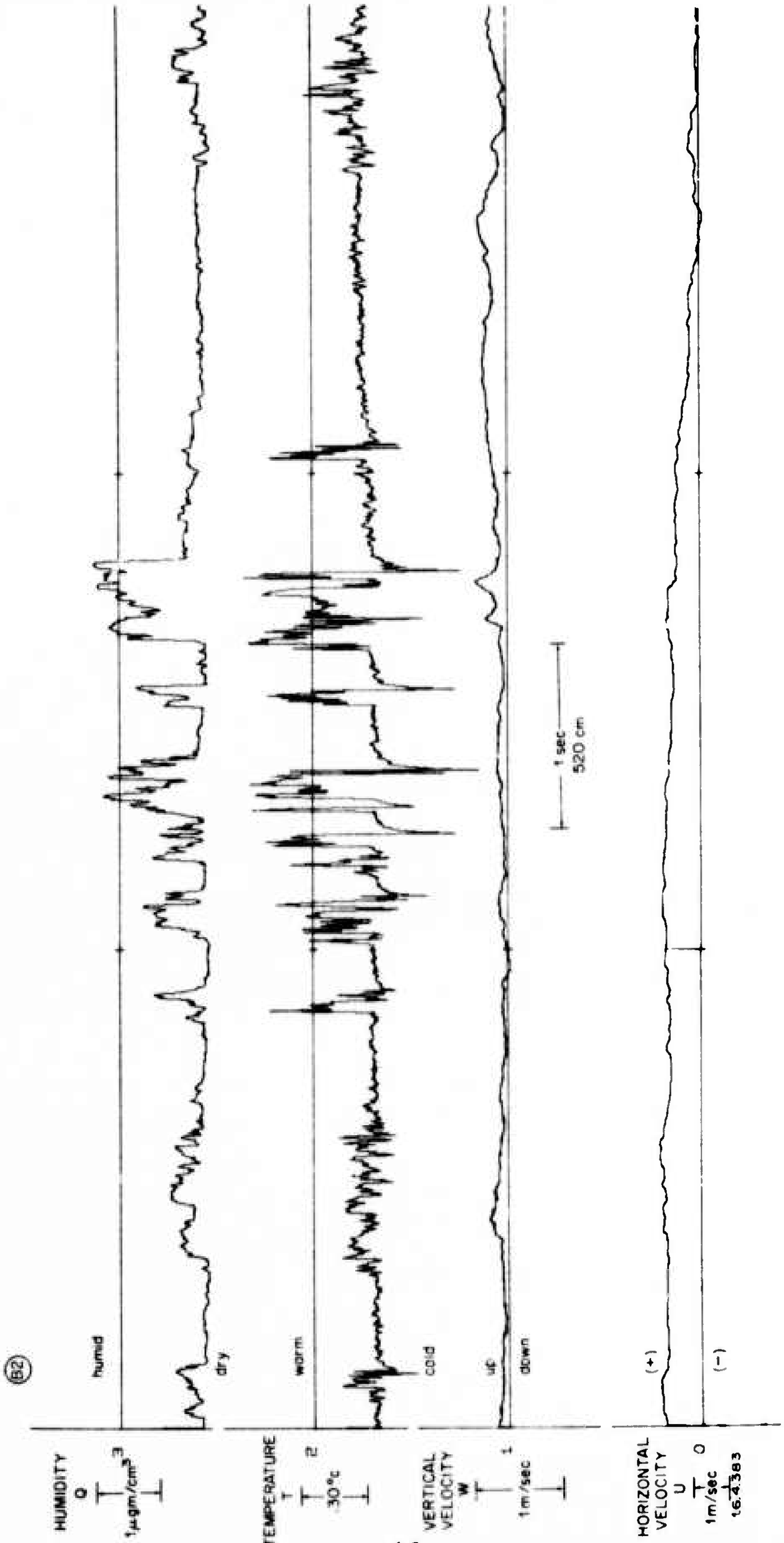
16.4.366
(+)
(-)
25 sec
130 meters

Figure 3

Figure 4: Expanded time series showing presence of "cold spikes" in the temperature signal.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30°c
VERTICAL VELOCITY
W
1m/sec
HORIZONTAL VELOCITY
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16.4.383

Figure 4

Figure 5a: Power spectra of turbulent velocity fluctuations obtained over the open ocean with a three-dimensional sonic anemometer. Slope of the solid line is -5/3 for the inertial subrange. The slight peaks in the spectra at $\sim 10^{-1}$ Hz may be caused by surface waves.

Figure 5b: Power spectra of temperature and humidity fluctuations obtained with a platinum cold wire sensor and a Lyman-alpha humidiometer. The humidity power spectrum follows the -5/3 slope, but the temperature spectrum does not. Overlapping spectral bands (two for humidity and three for temperature) were used to cover the large dynamic ranges of the signals. The frequency response of the temperature sensor is greater than that of the humidity sensor.

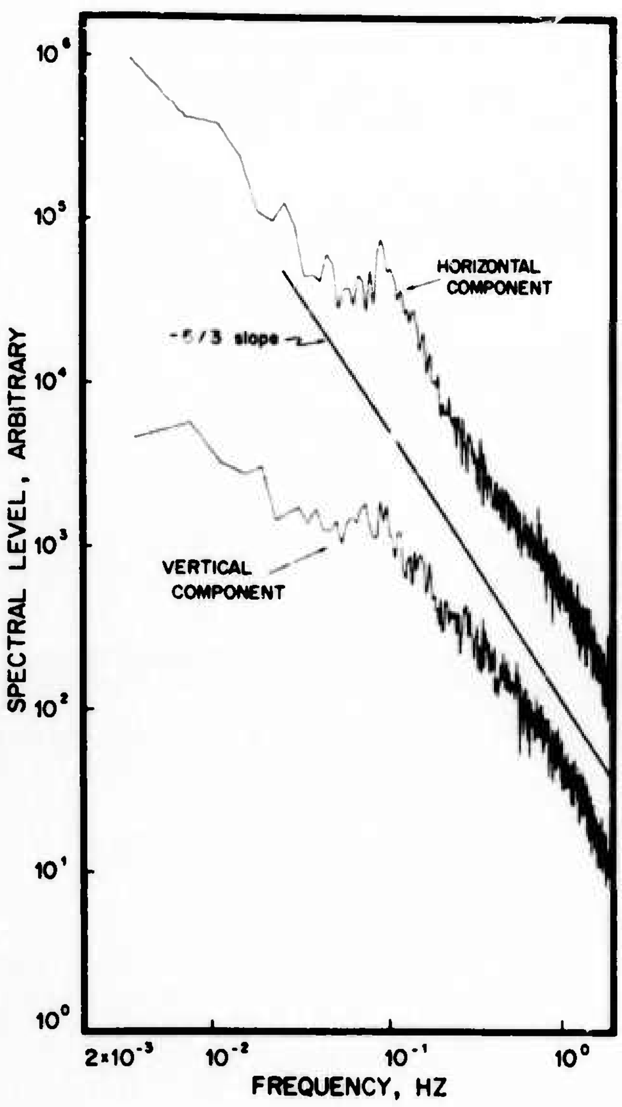


Figure 5a

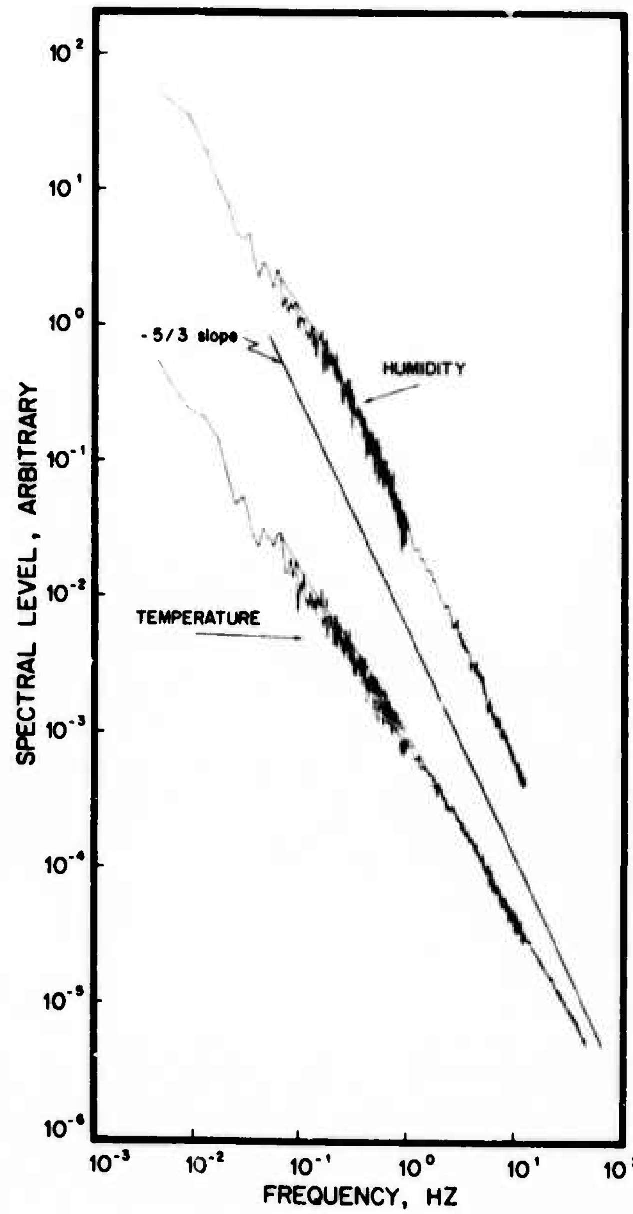
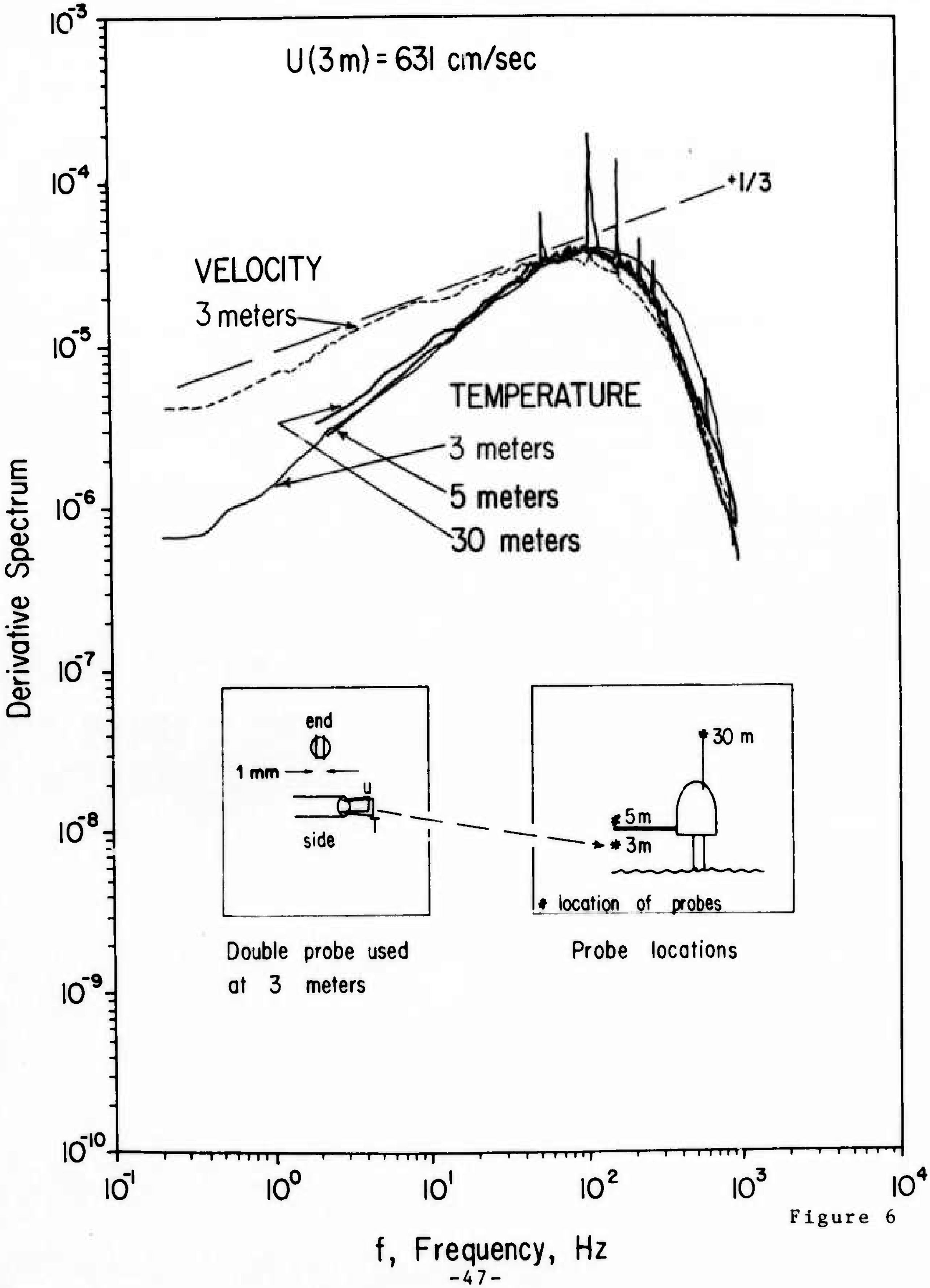


Figure 5b

Figure 6: Spectra of the time derivatives of velocity and temperature. The data at 3m height were obtained with a hot wire (velocity) -Pt cold wire (temperature) probe with 1 mm sensor separation. The Kolmogorov inertial subrange is given by a slope of +1/3 for the power spectrum of a derivative. The velocity exhibits an inertial subrange, whereas the temperature does not.



U(3m) = 631 cm/sec
VELOCITY
3 meters
+1/3
TEMPERATURE
3 meters
5 meters
30 meters
Derivative Spectrum
end
1 mm
u
T
side
Double probe used at 3 meters
30 m
5m
3m
* location of probes
Probe locations
f, Frequency, Hz

Figure 6

Attachment 2

ABSTRACT

Submitted to American Physical Society
Division of Fluid Dynamics
Twenty-Seventh Annual Meeting
25-26-27 November, 1974
California Institute of Technology
Pasadena, California

Topic Area: Turbulence Phenomena

Temperature Derivative Spectra Over the Open Ocean

by

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University of California, San Diego

For a passive scalar at high Reynolds number and at a Prandtl number ($Pr \equiv \frac{\nu}{D}$) near unity the temperature derivative spectrum should have a universal inertial subrange of slope + 1/3. The predicted form for the derivative spectrum is $\Phi_{\dot{T}}(k) = \beta\chi\varepsilon^{1/3}k^{1/3}$ where χ is the scalar dissipation rate, ε the viscous dissipation rate, κ is the wavenumber and β a "universal" constant. In the atmospheric boundary layer β is not constant and over the open ocean the slope of the derivative spectrum varies between 0.7 and the predicted value of 0.33. These variations in slope seem to be related to the background meteorological conditions, steeper slopes occurring under cool, dry conditions and slopes nearer =1/3 under warm, humid conditions. The evaporation of spray in the near water zone could cause variations in slope in conjunction with radiational effects due to high absolute humidities over the ocean.

Work supported by National Science Foundation (Atmospheric Sciences Section) Grant GA-41782, and Office of Naval Research Contract N00014-69-A-0200-6049, and the Advanced Research Project Agency, monitored by Office of Naval Research under Contract N00014-69-A-0200-6039.